PHYS 533: Nanostructures and Nanotechnology I, Fall 2020

Logistical details

Meets: 13:30-14:25, Mon/Wed/Fri for 55 min, with zoom simulcast and recording
Instructor: Prof. Douglas Natelson (BRK 301, x3214, natelson@rice.edu)
Grader: TBD
Office hours: TBD, via zoom and in-person in covid-safe ways. For additional time, my door is open, but you should email ahead to make sure that I'm around.
Webpage: https://canvas.rice.edu/courses/33458

What are nanostructures and why should you care?

A nanostructure is reasonably defined as an object possessing at least one critical dimension less than 100 nm in extent. By that definition nanostructured systems are all around us all the time and are already prevalent in technology. Molecules fit the bill, and chemists have effectively been performing nanoscience for many years, albeit with large numbers (10^{23}) of nanostructures.

The properties of matter on the nanometer scale can be vastly different than those on the macroscopic scale. The borders between physics, chemistry, and materials science become blurred, and lessons may also be learned from the nanoscience of living things, molecular biology. When matter is confined or structured on the nanoscale, some physics that matters little in bulk systems may dominate important properties like electrical conduction, mechanical strength, or equilibrium *structure*. The newly relevant physics may have its origins in classical effects: e.g. the classical charging energy of a capacitor may exceed the room temperature thermal energy scale if the capacitor is sufficiently tiny. Alternately, new phenomena can arise statistically from the reduction in N, the number of atoms, from a thermodynamically large value (10^{22}) to a small value (100): *e.g.*, as the surface to volume ratio for a metal cluster becomes very large, the thermodynamically stable crystal structure can change dramatically. Finally, quantum mechanical effects (e.g. tunneling, quantum interference), typically relevant at very short length scales, may become dominant when system sizes approach the nanometer regime.

Within the last 30 years, new tools have been developed that allow precise engineering of materials on scales approaching that of single atoms. Simultaneously, progress has created an ever-increasing demand for further miniaturization of existing technology, to the point that the physical principles on which that technology is based are at the edge of their validity. In some ways this is reminiscent of solid-state physics research in around 1950. Scientists are making gains in understanding the fundamental properties of these new systems; simultaneously they are making laboratory demonstrations of possible technological spin-offs; the path of industrial adoption of these systems is a long road; and forecasting the long-term industrial impact fifty years down the line is essentially impossible. It's a fairly safe bet, however, that the physics of nanostructures will continue to have a massive impact on all of us - as we'll see in this course, it already has.

Course objectives and learning outcomes

By the end of this course, students will be able to:

- Explain why nanostructuring a material allows deviations from the predictions of the electronic properties of bulk crystalline solids, including breaking conservation of crystal momentum.
- Describe multiple quantum corrections to (semi)classical conduction.
- Understand the Landauer-Buttiker picture of conduction.
- Explain the operating principles of field-effect transistors and effects that become relevant at small scales.
- Describe the origins of giant and tunneling magnetoresistance effects.
- Demonstrate the ability to read and critically analyze papers in the current literature that employ nanostructured materials and nanoscale devices.

Required text and materials

Textbook: *Nanostructures and Nanotechnology* (Cambridge 2015), Douglas Natelson.

I will supplement and update this book with additional material from a variety of sources, particularly the current literature. Feel free to pick up a used copy of the book.

Exams, papers, and grading

There will be (roughly) weekly problem sets, made available on Wednesday and due the following Wednesday at 5pm. Late work will only be accepted if due to illness or emergency - I want a legitimate excuse.

Understanding the material is at least as important as getting a numerically or formulaically correct answer to the problem. If your reasoning isn't obvious, please write little explanations of what you're doing and why, so partial credit can be assigned in a reasonable way.

Unsurprisingly, it's rather difficult to come up with lots of homework problems that are really relevant, produce physical insight when solved, and are tractable in a reasonable time frame. You will find that most of the problems I assign are not terribly calculationally intense, and some involve descriptive interpretation of what's going on, such as brief (3-5 sentence) responses. Learning to communicate your physical understanding through writing is an important and often neglected skill that is essential to develop.

The problem sets are not pledged. I encourage you to discuss the problem sets with each other. You may give each other guidance and advice on problem solving approaches, and you may compare solutions to check your work. However, you may not copy solutions from another student, and the problem sets you submit must be entirely your own work and your own words. *If you use a book, journal article, or website, you must cite the relevant material*. If you collaborated strongly with other students, cite them as well - this is intellectual honesty.

There will be no exams in the course. **Grading** will be:

- 50% homework
- 20% midterm paper

- 25% final paper
- 5% participation

The papers **will** be pledged. A list of possible topics will be released later in the semester, along with details of the format and style. These papers must be **your own work** - you **must cite** all sources used, and if you quote someone else's material, you must clearly indicate that. Here is a handy guide that explains the nature of plagiarism and how to avoid it: https://gpsdocs.rice.edu/orientation/Plagiarism_Hewitt_document.pdf. Plagiarism will **not** be tolerated and will be referred to the Honor Council. Treat this like a real-world document you'd be sending to referees, or like a technical memo you'd be sending to your boss. There are two papers because I think it's better to give you a chance to get some feedback on your writing rather than have it be a "fire and forget" process. At the beginning of the course, I will make you take a 1-question quiz on canvas indicating that you understand this. Experience has taught me that this is a good idea.

"Participation" is tough to quantify, but I want to encourage you to ask questions and discuss, particularly about the reading assignments. Trust me - if there's something in the course you find unclear, you're unlikely to be alone. Talking about these topics with each other and with me is a better way to learn the material than trying to do it in a vacuum.

Communication Plan

The course will consist of pre-recorded video material and reading material as well as three 55 minute lectures per week, planned for both in-person and zoom casting. These will be recorded and available via canvas, both for your review and for students who have to take the course asynchronously. I will also have online office hours (timing to be decided, depending on the registrar's final schedule).

I want to have a chat feature as well, so that the students can converse with each other as well as with me. I'm still deciding whether to use the chat feature of canvas, or to go with another tool such as slack.

Finally, I encourage students to reach out via email (natelson@rice.edu) to reach me.

Course Outline

A schedule of classes will be available on canvas and will be updated as the semester progresses. Roughly speaking:

- An introductory set of lectures introducing / reviewing key concepts from solid state physics so that we're all on the same page. The emphasis will be on where nanoscale structure has significant effects.
- Lectures introducing other framework topics not always covered in typical solid state courses, including: electronic transport in mesoscale and nanoscale systems; quantum interference effects; tunneling; quantum wells & dots; magnetic materials.

- Present day technology: transistor physics; state-of-the-art transistors; where are nanoscale effects relevant?
- Potential successors in the laboratory: "exotic" CMOS; molecular devices; a little on solid-state approaches to quantum information
- Present day technology: magnetic media and recording; where are nanoscale effects relevant?
- Potential successors in the laboratory: spintronics

Rice Honor Code

In this course, all students will be held to the standards of the Rice Honor Code, a code that you pledged to honor when you matriculated at this institution. If you are unfamiliar with the details of this code and how it is administered, you should consult the Honor System Handbook at http://honor.rice.edu/honor-system-handbook/. This handbook outlines the University's expectations for the integrity of your academic work, the procedures for resolving alleged violations of those expectations, and the rights and responsibilities of students and faculty members throughout the process. I take the Honor Code seriously, and I expect you to do the same. If you have any questions about this, raise them with me at the beginning of the course.

Disability support services

If you have a documented disability or other condition that may affect academic performance you should: 1) make sure this documentation is on file with Disability Support Services (Allen Center, Room 111 / adarice@rice.edu / x5841) to determine the accommodations you need; and 2) talk with me to discuss your accommodation needs.

Title IX responsible employee notification

Rice University cares about your wellbeing and safety. Rice encourages any student who has experienced an incident of harassment, pregnancy discrimination or gender discrimination or relationship, sexual, or other forms interpersonal violence to seek support through The SAFE Office. Students should be aware when seeking support on campus that most employees, including myself, as the instructor/TA, are required by Title IX to disclose all incidents of non-consensual interpersonal behaviors to Title IX professionals on campus who can act to support that student and meet their needs. For more information, please visit safe.rice.edu or email titleixsupport@rice.edu.

Standard disclaimer

The instructor has the authority to rule on any point not covered in this syllabus. The syllabus is subject to change at the discretion of the instructor. Students will be notified before any changes take effect.

Additional reference material

Solid-state physics texts

- Steve Simon. *The Oxford Solid State Basics*. This is a very good solid-state book at the undergrad level. The lectures are available online, and Prof. Simon has posted more advanced material as well.
- Steve Girvin and Kun Yang. *Modern Condensed Matter Physics*. This text came out in 2019, and is the best candidate I've seen to replace Ashcroft and Mermin (below) as the standard graduate level text in this area.
- N. Ashcroft and N.D. Mermin. *Solid State Physics*. The classic graduate text. Excellent, and as readable as any physics book ever is. Too bad that it ends in the mid 1970's....
- D.L. Goodstein. *States of Matter*, Dover. Excellent, but somewhere between a stat mech and a solid state text. It's very readable, and a very good deal since it's a Dover book.
- P.M. Chaikin and T.C. Lubensky. *Principles of Condensed Matter Physics*. Cambridge University. Has very good chapters on phase transitions. Avail. in paperback, so it's not absurdly expensive.
- Michael P. Marder. *Condensed Matter Physics*. Wiley. A very comprehensive newer book, intended as a more current alternative to Ashcroft and Mermin. Rather encyclopedic.

Nanoscience and device-related books

- Supriyo Datta from Purdue has written multiple books on nanoscience that are all quite good, with slightly different emphases:
    - *Lessons from Nanoelectronics: A New Perspective on Transport*
    - *Quantum Transport: Atom to Transistor*
    - *Electronic Transport in Mesoscopic Systems*
- Yoseph Imry, *Introduction to Mesoscopic Physics*. For those interested in quantum corrections to classical conduction, this is a classic. It is terse.
- Max Di Ventra, *Electrical Transport in Nanoscale Systems*. This work focuses on the theory of nanoscale transport at the grad level.
- Stuart Lindsay, *Introduction to Nanoscience*. This takes a more chemistry-oriented perspective.
- Geoffrey Ozin, *Nanoscale Chemistry: A Chemical Approach to Nanomaterials*. This is a very valuable perspective on the emergent properties of materials at the nanoscale.
- Guozhong Cao and Ying Wang, *Nanostructures and Nanomaterials*. Likewise, this is a very materials-focused look at nano.
- S. M. Sze and Kwok K. Ng, *Physics of Semiconductor Devices*. This book is the standard on this topic – contains a wealth of knowledge.
- Robert F. Pierret, *Advanced Semiconductor Fundamentals* and other books in this series. This is a very nice intro aimed at EE undergraduates.

Updated: July 17, 2020